



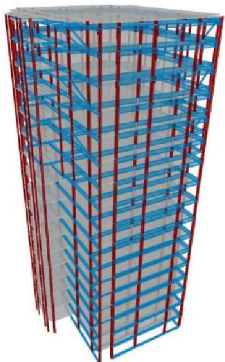
The UCLA Factor Building Seismic Array Monitoring Structural State of Health

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The development of robust designs in seismometer hardware and software is making it more feasible to densely instrument civil structures on a permanent basis in order to study their states of health. The 17-story UCLA Factor building contains one of those cutting-edge structural arrays, recording building vibrations continuously at high sample rates. It is one of only a handful of buildings in the U.S. permanently instrumented on every floor, providing us with information about how a common class of urban structures, mid-rise moment-frame steel buildings, will respond to strong ground shaking and how the response changes as the building is damaged. For example, structural stiffness undoubtedly decreased when welded beam-column connections extensively fractured in numerous moment-frame steel buildings during the 1994 Northridge earthquake. Unfortunately, there are no seismic records from buildings with this type of damage. However, we anticipate that changes should be observable through analysis of vibration data for a well-instrumented building.

In state-of-health monitoring of engineered structures, determining how structural properties change with excitation amplitude, time, and other geophysical and environmental conditions constitutes a major research challenge, especially as the changes relate to rapid damage assessment. Methodologies to design earthquake-resistant buildings are ever-evolving with new understanding of how earthquake shaking impacts a building. While we wait for the infrequent, large amplitude shaking events to record nonlinearities, we are using the valuable, small-to-intermediate amplitude data to characterize the linear behavior of the building-soil system. To complement the data gathering, we have constructed a

three-dimensional model of the Factor building based on structural engineering



Finite-element model of the Factor building showing the major structural features. The model is based on object-based elements such as columns, moment-frame beams, slabs, walls, and beam-column intersections whose properties were obtained from structural engineering drawings (printed with permission from BSSA).

drawings for dynamic analysis of building response to observed and scenario excitation. In a sense, working with the Factor building array is analogous to collecting global seismological data that are evenly distributed over Earth's entire surface and having access to an accurate 3D starting model of Earth structure at relatively small length scales.

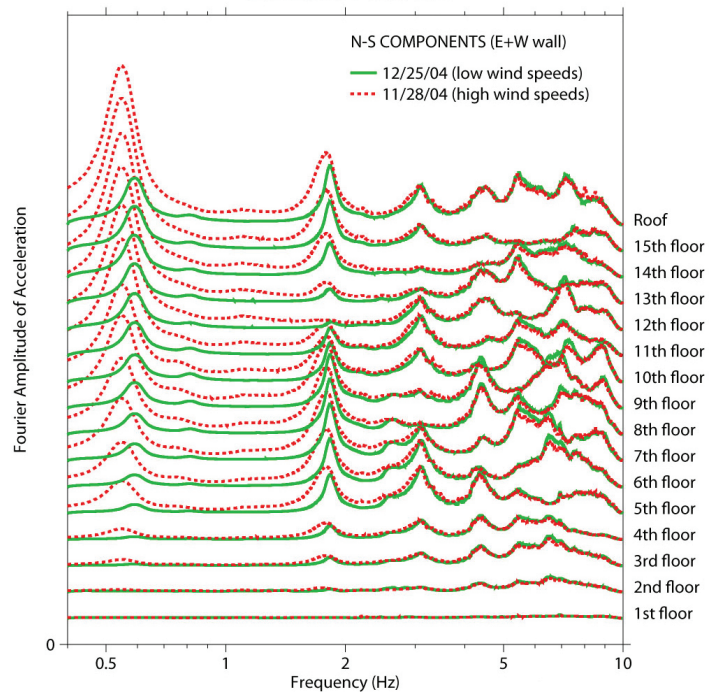
THE FACTOR BUILDING ARRAY

The Factor building is a prototype USGS Advanced National Seismic System instrumented structure for use in structural health monitoring and engineering research applications. The building array comprises 72 channels distributed four per floor and the roof. The horizontal sensors are oriented north-south and east-west along the mid-sections of most floors. GPS receivers for timing are located on the roof. Six channels from nearby down-hole and surface borehole seismometers, and four free-field stations are contributing data to characterize input ground motions and the dynamic interactions between the building and the underlying soils. Two borehole seismometers (one at the surface and one at 100 m depth) are located 25 m east of the Factor building in the UCLA Botanical Gardens. Each consists of a three-component accelerometer connected to a 24-bit digitizer located in a garden shed a few meters from the borehole. The borehole and free-field data are being piped directly into a real-time system controlled by the monitoring software. Two

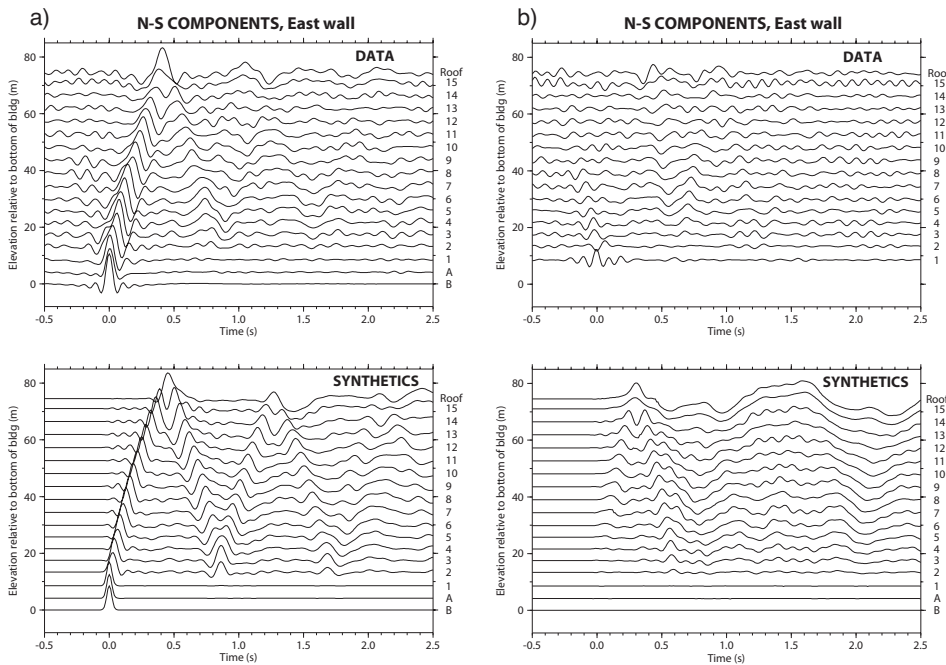
GPS antennas were installed on the roof to test the continuous recording of building displacement and inter-story drift.

In the building's attic, nine 24-bit digitizers record the continuous data in two data streams: one at 100 sps for long term archiving and one at 500 sps on a RAID array from which local and regional earthquakes are being extracted. The data are recorded both on-site and in the seismology laboratory at UCLA. A dedicated fiber optic Internet connection within the Factor building enables continuous data flow from Factor into other laboratories. The building and borehole data can be viewed from the Factor array web site <http://factor.gps.caltech.edu/>.

Fortunately, the IRIS DMC has made archival and subsequent retrieval of the data for general engineering research convenient. The 100 sps data are being archived at the IRIS DMC in miniSEED format and are immediately available for request. The DMC also has the metadata for use in generating the miniSEED files, and for conversion to other data formats. →



Ambient vibration spectral data from the Factor building for two 24-hour periods: one windy day (November 28, 2004) showing a decrease in the north-south horizontal modal frequencies, and one calm day (December 24, 2004). Each curve consists of stacked spectra from one-hour time series. Maximum average wind speeds recorded nearby on the UCLA campus on November 28, 2004 were 25 mph, and gusts were nearly 40 mph.



The north-south translational (left) and torsional (right) response functions for a north-south impulse at the base of the building. These responses were computed from 100-s time series that contained the initial shear wave for earthquakes. The records were bandpass filtered for frequencies between 2.0 and 10.0 Hz to isolate the shear waves whose propagation effects dominated building response. Records for upper floors were each deconvolved by the subbasement record which served as the approximate source input impulse function. Twenty individual impulse response functions were then stacked and compared with simulations using 2% modal damping with a Gaussian curve input in the north-south direction (printed with permission from BSSA).

The DMC has data starting in mid-2005. Eventually the earlier waveform data will be transferred to the DMC.

STRUCTURAL HEALTH MONITORING

With the availability of high-quality building waveform data, structural health monitoring research is making more frequent use of wave propagation methods, in addition to the more traditional modal methods. The combination of frequency change information coupled with that provided by wave propagation properties could constitute the elements of tools for real-time damage detection in instrumented buildings. Towards that end, we are using both time and spectral domain representations of real and simulated building response to understand the relationship between damage patterns and motions recorded in the building.

A tremendous advantage of building waveform data is the ability to observe translational, rocking, and torsional (twisting) motions which can be significant for this type of structure. Torsional motions (including approximate torsions calculated from pairs of recordings) are rarely recorded in buildings; thus their importance in redesigning building codes is often underestimated [Chopra, 2001]. We

have used a technique similar to Green's functions to characterize waves that propagate through the Factor building. Impulse response functions of a building theoretically represent only the building property effects on the wave propagation between receivers. In the case of the Factor building, we obtain an approximate impulse source by deconvolving the subbasement waveform from the upper floors.

We computed the impulse response functions for small and intermediate-size earthquakes recorded by the Factor array, and stacked the resulting waveforms [Kohler *et al.*, 2007]. The stacked results are compared to synthetic waveforms computed for our finite-element model of the building, calibrated with the recorded earthquake data. Both the impulse response functions from the data and the dynamic analysis synthetics show the impulsive shear waves traveling up and down the building. They also show a reflection of the initial upgoing wave from the bottom of the 10th floor for the east-west component of the motion. The building has cantilevered, overhanging sections between the 10th floor and roof on the east and west faces that are supported by diagonal steel braces. They stiffen the upper floors of the building against inter-story shearing in the east-west direction. In effect,

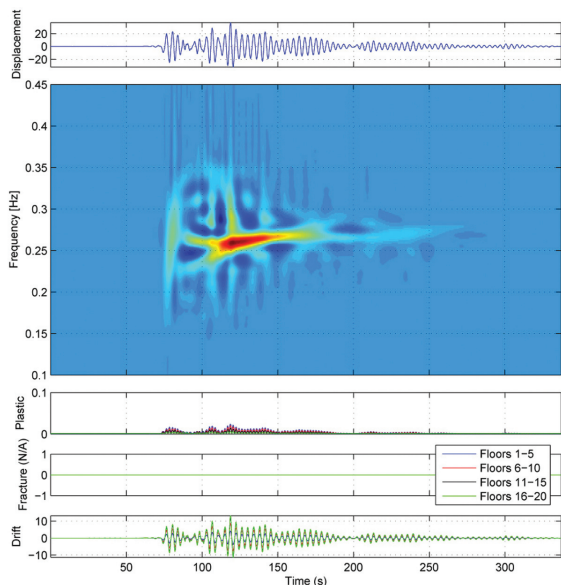
the shear-wave velocity (approximately 150 m/s for a vertically propagating SH wave) increases at the 10th floor.

Both data and synthetics show asymmetry in the excitation of vertically-propagating torsional waves. These torsional waves are due primarily to inter-story shearing in which floors rotate about a vertical axis; this rotation can be obtained by differencing identical components of motions recorded at opposite ends of any floor. When the ground motion is an east-west impulse, the torsions begin immediately at the first floor and then propagate up the building. However, when the ground motion is a north-south impulse, torsional waves do not begin appearing until the north-south shear waves reach the upper floors. The asymmetry in the excitation of torsional motions is probably due to the fact that the building foundation is embedded in the soils of a south-sloping hillside, which means that the ground-level story effectively has a shear wall only on the north face. It may be possible in the future to identify additional torsional motions due to specific types of damage such as cracked welds in one region of a structure. The resulting changes in stiffness may give rise to changes in torsional modes.

We are also investigating new ways to more accurately pinpoint the time at which deviations from linearity occurred as a signature of significant structural damage. Measurable nonlinear effects are occurring for small-to-intermediate earthquake and wind excitation that cause changes in the stiffness of the Factor building-soil system [Kohler *et al.*, 2005]. Modal frequency data show a decrease in frequencies during the shaking events, returning to previous ambient vibration levels soon after the cessation of the shaking.

We have begun to develop a new tool that provides a better compromise between frequency and time resolution than that produced by familiar spectrogram and wavelet techniques [Bradford *et al.*, 2006]. The new tool, based on the Wigner-Ville distribution from quantum mechanics, is a nonlinear transformation that provides a view of the time-frequency decomposition that is more suitable for instantaneously analyzing the changing frequency content in a signal. While the Wigner-Ville distribution provides extremely high resolution, it comes at the expense of interference terms which can be reduced by appropriate filtering. →

In order to assess the usefulness of this new tool, we have applied it to a finite-element model of a 20-story steel frame building that includes material and geometric nonlinearities, plastic steel rheology, and weld fractures. We simulate the inertial motions of every location in the building while also keeping track of the structural characteristics of the building (*e.g.*, plastic rotations, weld fractures). Simulations of the model building subjected to simulated, full-scale and scaled-down motions of the 2003 M_w 8.2 Tokachi-Oki earthquake result in linear and nonlinear behavior whose differences are immediately obvious. The near-linear response for the scaled-down input is



Simulated, time-dependent frequency response (reduced interference Wigner-Ville distribution) of a 20-story steel frame building using scaled-down (left) and full-scale (right) motions of the 2003 M_w =8.2 Tokachi-Oki earthquake. The near-linear response (left) is dominated by the fundamental mode of the building, while the nonlinear response (right) shows a marked decrease in building frequency and the generation of an additional modal frequency due to the damaged elements.

dominated by the fundamental mode of the building. However, the nonlinear response for the full-scale input shows a steep decrease in the building frequency during plastic deformation. The nonlinear building develops additional peaks in the waveforms that show up as the two frequencies identified by the new frequency-time algorithm. The long-term goal is to run algorithms based on techniques such as this on embedded structural arrays in order to make near real-time assessments of structural integrity.

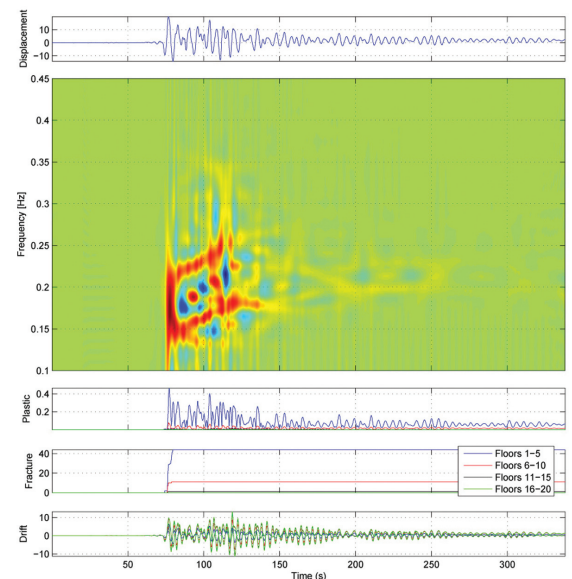
FUTURE SOFTWARE AND HARDWARE DEVELOPMENTS USING THE DATA

We are now using our building model to develop a quantitative method of identifying modal and wavefield characteristics from a “damaged building” (*e.g.*, simulated combinations of broken welds, damaged columns, asymmetrically weakened structural elements) to determine what is realistically observable for dam-

age detection tools. This is where the big challenge lies because it is not clear yet how to address the non-uniqueness of this problem or how to combine the results of numerical modeling in an all-encompassing tool for damage detection. However, because the ability now exists to calibrate the finite-element model with observed earthquake data, damage simulation results can be produced with increased modeling and statistical rigor.

Truly useful structural health monitoring networks need to be designed with processors that can support the execution of algorithms based on damage detection research such as that described here.

locations easier [Gnawali *et al.*, 2006]. The higher-level nodes could include a processor on which the algorithms would run continuously, reporting back to a central unit. Lower, more primitive nodes would simply consist of the sensor and digitizer, but these would be in constant communication with at least one higher-level node. The results of the networking software could be used to redeploy nodes during aftershock sequences in areas where significant damage is suspected. The Factor array is being used in side-by-side tests of structural monitoring wireless network hardware and software that have the potential of accomplishing many of these long-term goals. ■



However, the process of installing wired networks in structures in heavily populated urban settings such as Los Angeles can take years because of difficulties in obtaining appropriate funding to cover the costs (typically hundreds of thousands of dollars per structure), seeking owner permission, and installing the sensing and communication hardware. Logistical limitations increasingly point to the need for a relatively inexpensive, low-power, easy-to-install network that can complement existing wired networks. This is particularly critical for deployments that are to take place in multiple structures on varying length scales for monitoring and damage assessment.

If we are to reach the goal of quickly deploying dense structural monitoring networks after a large earthquake has occurred, we need to consider innovative hardware and software designs. For example, a network that consists of two levels of complexity would make network reconfiguration based on suspected damage

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